

DSMS Telecommunications Link
Design Handbook

304

Frequency and Timing

Document Owner:

Approved by:

B. Benjauthrit
Frequency and Timing
System Engineer

Date

R. L. Tjoelker
Frequency and Timing Service
System Development Engineer

Date

Released by:

[Signature on File]
[at DSMS Library]

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Note to Readers

There are two sets of document histories in the 810-005 document that are reflected in the header at the top of the page. First, the entire document is periodically released as a revision when major changes affect a majority of the modules. For example, this module is part of 810-005, Revision E. Second, the individual modules also change, starting as an initial issue that has no revision letter. When a module is changed, a change letter is appended to the module number on the second line of the header and a summary of the changes is entered in the module's change log.

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1 Introduction

1.1 Purpose

This module provides information to assist Deep Space Mission System (DSMS) customers in understanding the fundamental limits placed on navigation, quality of science observations, and telecommunications performance by the Frequency and Timing Subsystem (FTS) equipment installed in the Deep Space Network (DSN).

1.2 Scope

The discussion in this module is limited to the accuracies and stabilities of frequency and time within the DSN including the effects of implementations that are unique to each site. The module deals primarily with general system information of the operational DSN FTS capability. Performance information that pertains only to specific users, such as performance for the radio science community, may be found in the modules for these topics. A brief discussion of proposed enhancements is included at the end of the module.

2 *General Information*

Figure 1 provides an overview of Frequency and Timing in the DSN. The three Deep Space Communications Complexes (DSCCs) have at least four Atomic Frequency Standards (AFSs) while other sites, with the exception of MIL 71, have one or two. MIL 71 receives its frequency and time references from Goddard Space Flight Center (GSFC) equipment that is co-located at the site.

At each major location, a single atomic frequency standard serves as the source for all coherent, precision frequencies and provides the reference for the station master clock. The other AFSs serve as backups should the selected reference fail or indicate instability. Each station synchronizes its clock to the National Institute of Standards and Technology (NIST) realization of Coordinated Universal Time (UTC), referred to as UTC (NIST), via the Global Positioning Satellite System (GPS). Time offset data measured at the DSCCs are forwarded to the DSN Time Analyst at JPL who is responsible for determining that FTS at the three complexes is performing correctly. The frequency and time performance for the test facilities is the responsibility of their respective operations organizations.

2.1 *Functions*

The FTS provides the following major functions:

- 1) Generate and distribute very stable reference frequencies, time codes, and timing pulses to other equipment
- 2) Provide measurements of clock synchronization (time) and syntonization (frequency) traceable to UTC (NIST)
- 3) Generate phase calibration tones for Very Long Baseline Interferometry (VLBI) via Phase Calibration Generators

2.2 *Components*

Principal components of the FTS include frequency standards, clocks, frequency and time distribution equipment, and phase calibration generators.

2.2.1 *Atomic Frequency Standards*

Three types of atomic frequency standards are deployed at the DSCCs. They are the hydrogen maser, the cesium-beam standard, and the linear (Mercury) ion trap standard using a high quality voltage-controlled (quartz) crystal oscillator (LITS/VCXO). The performance of these standards is a function of multiple factors including model, configuration, and the environment. Figure 2 shows the range of performance routinely available in the DSMS in terms of Allan Deviation, σ , over the averaging time, τ . The lower bound of the range in the figure captures the optimum performance that should be expected in the implemented configuration. The upper bound can be considered as the worst case. This figure also shows the performance of the Compensated Sapphire Oscillator (CSO), a non-atomic oscillator that is discussed below.

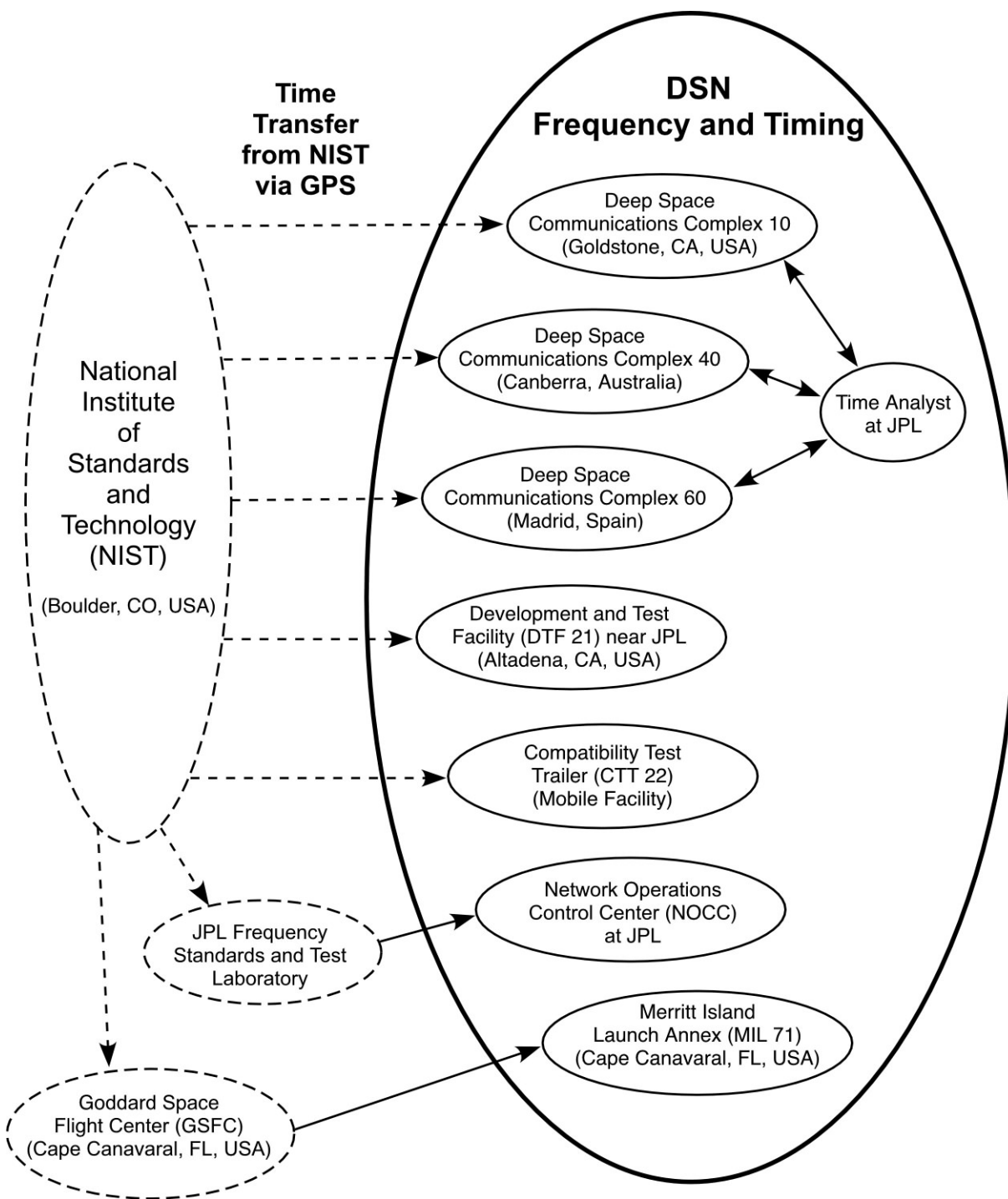


Figure 1. DSN Frequency and Timing.

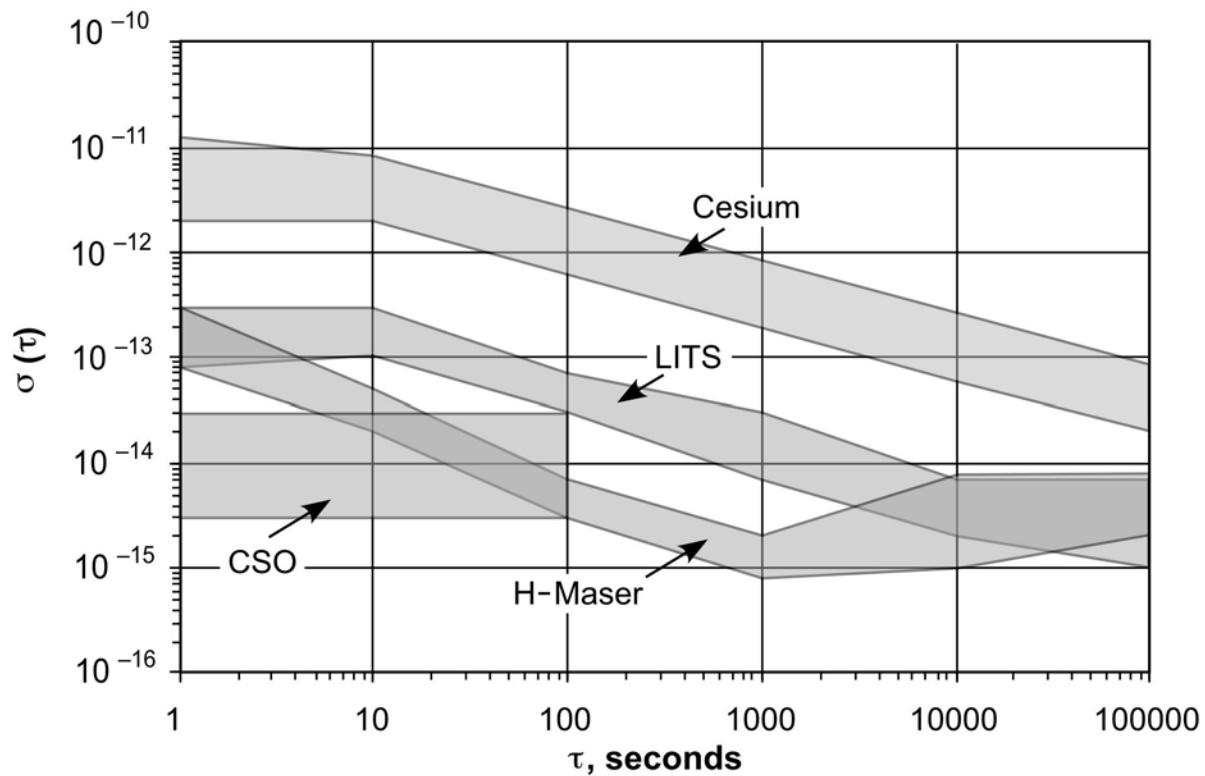


Figure 2. Allan Deviation of Frequency Standards.

Hydrogen masers have been employed as the main DSMS frequency standard for some years. They provide spectral purity commensurate with a very good quartz crystal oscillator and frequency stability that is appropriate for measurement periods of up to 1000 to 10,000 seconds. Recently, the hydrogen masers have been supplemented with LITS/VCXOs that provide excellent stability at both short and long integration times and stability between that of a hydrogen maser and a cesium standard at short to moderate integration times.

Spectral purity is especially important because the frequency standard must be multiplied to DSMS transmit and receiver local oscillator frequencies and the multiplication degrades the spectral purity (expressed as a signal-to-noise ratio) by 6 dB per octave or 20 dB per decade. Noise injected by a local oscillator has the same effect on receiver performance as noise from any other source and can significantly degrade radio science investigations. Stability for measurement times through 10,000 seconds is important for navigation, where frequencies are compared delayed by the round-trip light time to the spacecraft. Another driver for stability at medium-to-long measurement times is radio science and VLBI investigations that normally are performed over a period of 8 to 12 hours. Table 1 summarizes the performance of the DSN frequency standards in the implemented configuration.

Table 1. DSN Frequency Standard Performance.

Parameter	Value
Reference Frequency Uncertainty (Allan Deviation)	
During routine periods (3 σ)	$\pm 9 \times 10^{-13}$
Typical (3 σ)	$\pm 3 \times 10^{-13}$
Reconstructed by analysis (3 σ)	$\pm 1 \times 10^{-13}$
Fractional Frequency Drift	
Specified	1×10^{-13} /10 days
Typical	$< 3 \times 10^{-14}$ /10 days
Harmonic distortion (sine waves)	$< 5\%$
Stability (Allan Deviation)	See Figure 1
Phase Noise at 100 MHz (unless otherwise specified)	In 1 Hz Bandwidth, 1 Hz from carrier. For other frequencies varies by $20 \log (f_{\text{desired}}/100)$
Hydrogen Maser	-97 to -104 dBc/Hz
Cesium Standard	-65 to -85 dBc/Hz
LITS/VCXO	-99 to -104 dBc/Hz
DSS 24 and DSS 27 at 5 MHz	-121 dBc
DSS 24 and DSS 27 at 100 MHz	-96 dBc
Frequency Offset Relative to UTC	
Maintained	$< 9 \times 10^{-13}$
Knowledge	$< 3 \times 10^{-13}$
Availability	> 0.9999

2.2.2 Complex Frequency Standards

The present complement of standards at each complex comprises two hydrogen masers, a Cesium standard, and a LITS/VCXO. The standards are located in an environmentally controlled area of the Signal Processing Center (SPC) at each DSCC.

2.2.3 Other Frequency Standards

In addition to the complex frequency standards, additional frequency standards are used by the DSN as described below.

2.2.3.1 *DSS 16 Frequency Standard*

DSS 16 at the Goldstone DSCC normally receives its frequency reference from the atomic standard in-use at SPC 10 via a fiber optic link. A cesium standard is maintained at the station to provide frequency references should there be a failure in the fiber optic equipment. Switchover from the SPC 10 reference to the local reference occurs automatically using a 5 MHz flywheel to provide a phase-continuous transition.

2.2.3.2 *DSS 25 Compensated Sapphire Oscillator*

Cryogenic oscillators provide the best ultra-high short-term stability and low phase noise available today for measurement times less than 200 seconds but are limited to laboratory environments by their dependence on liquid Helium. The Compensated Sapphire Oscillator provides performance approaching that of laboratory cryogenic oscillators while permitting long-term operation associated with commercial cryogenic cooling systems. A CSO has been installed at DSS 25 to provide a suitable reference for radio science investigations requiring the performance shown in Figure 2.

2.2.3.3 *Frequency References for Test Facilities*

Reference frequencies at the Development and Test Facility, DTF 21, and the Compatibility Test Trailer, CTT 22, are provided by a local standard consisting of a quartz crystal oscillator synchronized to a GPS receiver. For testing at DTF 21 that requires higher performance, a signal from a hydrogen maser, similar to those used at the complexes, can be made available from the JPL Frequency Standards and Test Laboratory (FSTL) via a fiber optic link. The calibration of this hydrogen maser can be traced to UTC via GPS.

Precision frequencies at MIL 71 are derived from the Goddard Space Flight Center frequency standard that is based on a commercial cesium-beam standard and a GPS receiver backup and has an accuracy of 5 parts in 10^{12} . The DSMS Network Operations Control Center (NOCC) does not require reference frequencies

2.2.4 *Reference Frequency Distribution*

Reference frequencies are distributed by a system of high-quality frequency synthesizers, distribution amplifiers, and cables that are designed to minimize degradation to the frequency standard performance. Reference frequency distribution at the DSCCs and other facilities are implemented as discussed below.

2.2.4.1 *Signal Processing Centers*

The outputs from the selected standard are routed from the frequency standards room to an assembly within the SPC control room referred to as the *Coherent Reference Generator* (CRG). The CRG provides distribution to all control room equipment.

2.2.4.2 *34-m High Efficiency Antennas and 70-m Antennas*

The frequency references for the receiver downconverters at the 34-m High Efficiency (HEF) and 70-m antennas are provided by a fiber optic transmission system, the *Fiber Optics Distribution Assembly* (FODA), designed to preserve the stability equivalent to that of a hydrogen maser at the distribution point within the antennas. The FODA installation at these stations uses special low temperature coefficient fiber optic cabling to transport the reference from the SPC to the tilting structure of the antennas. This is important because the cables on the antennas are exposed to the desert environment and can experience significant changes in temperature both from the environment and when antenna motion exposes them or shields them from the sun.

2.2.4.3 *34-m Beam Waveguide Antennas*

The frequency references for the receiver downconverters and Ka-band equipment at the 34-m Beam Waveguide (BWG) antennas are provided by FODAs at all antennas except DSS 24 and DSS 27. Standard temperature coefficient fiber is used however it is buried 1.2 m below the surface where there are no significant diurnal changes for antennas located near the SPCs. All equipment at the BWG antennas is located within the antenna pedestals so antenna motion has no effect on frequency stability.

Three of the beam waveguide antennas at the Goldstone DSCC are located 15.5 km from the SPC and the fourth, DSS 27, is located 30 km from the SPC. Although the fiber optic cable is 1.2 m below the surface, a diurnal change of 2.5-degrees at 100 MHz over a 12-hour period has been observed at DSS 24. The reference for the co-located DSS 26 is expected to experience a similar variation as its reference fiber is part of the same buried cable bundle. The diurnal phase delay at DSS 27 is expected to be 5 degrees at 100 MHz because its distance from the SPC is approximately twice that of DSS 24 and DSS 26.

The third antenna in the three-antenna BWG cluster at the Goldstone DSCC, DSS 25, has been equipped with a stabilized FODA (the SFODA) that uses a return signal to actively compensate for the diurnal phase change. As a result, the phase change at DSS 25 is less than 0.002 degrees at 100 MHz over a 12 hour period. The principal use of the SFODA is to steer the frequency of the CSO at DSS 25 thereby improving its stability at longer integration times.

The frequency references for the receiver downconverters at DSS 24 and DSS 27 including the Ka-band equipment planned for DSS 24 are provided by a lower quality fiber optics transmission system than at the other antennas. This system operates at 5 MHz rather than the 100 MHz used by the FODAs and causes some degradation to both the Allan Deviation and phase noise of the frequency references at these sites. Figure 3 provides the measured Allan Deviation for DSS 24 and the estimated Allan Deviation for DSS 27.

2.2.5 *Time Standards*

All DSN facilities use a single time source, traceable to UTC, for all equipment and operations within the facility. The accuracy and availability of this time source depend on the requirements of the facility at which it is installed.

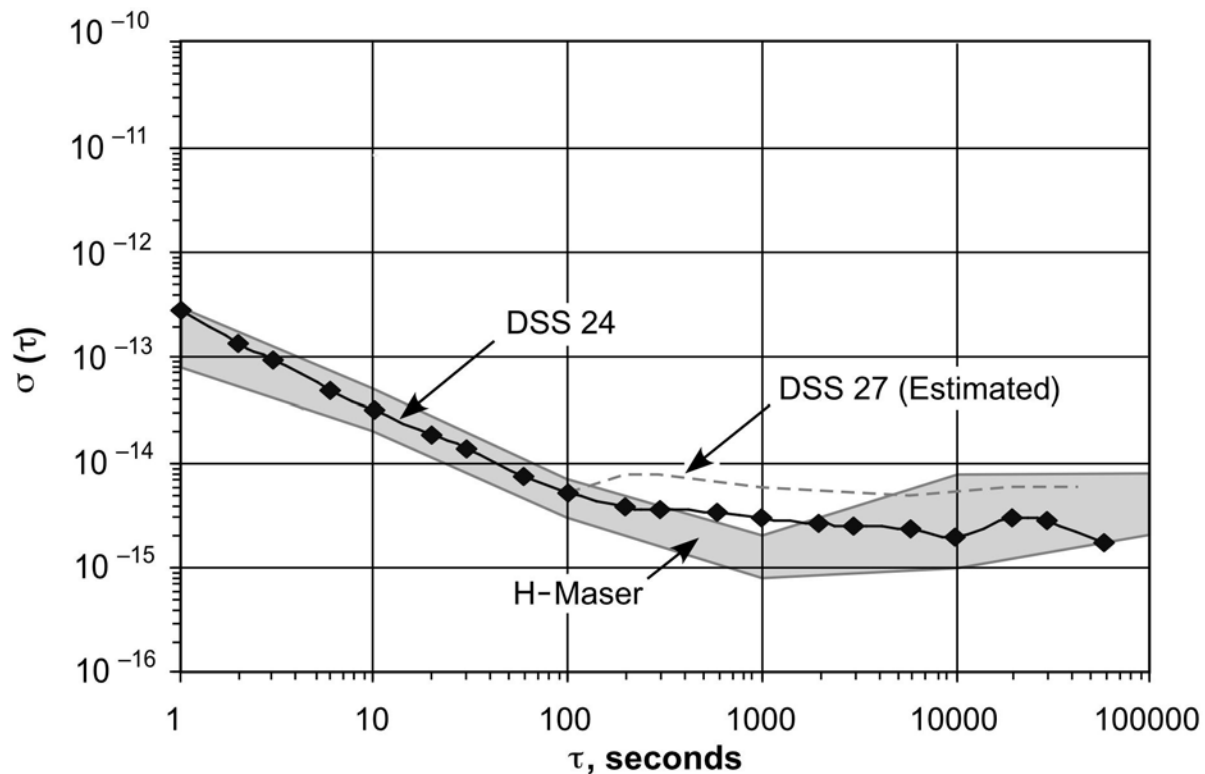


Figure 3. Allan Deviation for DSS 24 and DSS 27 Antennas.

2.2.5.1 DSCC Time Standard

Each DSCC contains a triply-redundant master clock with majority vote to identify a defective clock or to initiate automatic switch-over to a correctly performing clock. Each of the three clocks operates from the selected station frequency standard. Should a switch of standards occur, the clocks briefly operate with an internal crystal oscillator, and then slew to the phase of the new standard as soon as switchover is complete. This technique ensures that the maximum clock error after a frequency standard failure does not exceed a clock cycle (200 ns with a 5 MHz reference). Characteristics of the DSCC Time Standard are provided in Table 2.

Time offset from UTC (NIST) is kept $< 12 \mu\text{s}$ though typically, the master clock is $< 3 \mu\text{s}$ from UTC with a knowledge $< 20 \text{ ns}$. Synchronization between the DSCCs and UTC is accomplished using common view GPS time transfer between NIST in Boulder, Colorado and the DSCCs. In the case of the Canberra DSCC (where there is inadequate common view to NIST or to another DSCC), the NIST radio station WWVH in Hawaii is used as a mapping reference to compare SPC 10 and SPC 40.

Table 2. DSCC Time Standard Characteristics.

Parameter	Value
Time Reference	UTC (NIST)
Setability	100 ns
Offsets	
From UTC (3σ)	$< 12\ \mu\text{s}$
Between DSCCs, requirement (3σ)	$< 9\ \mu\text{s}$
Between DSCCs, typical (3σ)	$< 3\ \mu\text{s}$
From UTC, reconstructed by analysis (3σ)	$< 1\ \mu\text{s}$
Between DSCCs, reconstructed by analysis (3σ)	$< 100\ \text{ns}$
Availability	> 0.9999

2.2.5.2 *DSS 16 Time Standard*

DSS 16 normally receives its time reference via a fiber optic link as a 36-bit serial time code from the master clock at SPC 10. This reference is used to synchronize several time code generators that operate off the local 5-MHz reference. Should a failure occur in the fiber optic link, these generators will continue to generate time codes and timing pulses based on the last known time reference to an accuracy of $\pm 500\ \text{ns}$. A cesium traveling clock is used to periodically “jam-start” the time code generators and align them to the SPC 10 master clock.

2.2.5.3 *DTF 21, CTT 22, and NOCC Time Standards*

Timing signals and date at DTF 21 and CTT 22 are derived from GPS receivers that reference GPS Time and traceable to UTC with an accuracy of $\leq 100\ \text{ns}$.

Time and date at the NOCC are obtained via the Network Time Protocol (NTP) that is derived from UTC by the JPL Calibration Lab. The time is referenced to GPS Time and is traceable to UTC with an accuracy of $\leq 100\ \text{ns}$. The NTP protocol enables all computers at NOCC to be synchronized within 0.1 s of UTC.

2.2.5.4 *MIL 71 Time Standard*

Precision timing signals at MIL 71 are derived from the Goddard Space Flight Center time standard that is synchronized to UTC within $\pm 10\ \mu\text{s}$ by a GPS receiver. The station also has LORAN-C and WWV receivers to provide backup time synchronization. The time uncertainty when using either of these backup receivers is $< 20\ \text{ms}$.

2.2.6 *Time Distribution*

Timing signals are distributed up to 30 km from each master clock by time code translators (TCTs) installed in individual items of equipment. The timing system can remove distribution path length delays with a resolution of 100 ns so the offset knowledge of synchronization to a specific user is < 100 ns.

Time and date used by the monitor and control computers for logging of station events are provided by NTP and derived from a TCT installed in one of the computers. The accuracy of this time is within 0.1 s of UTC however station logging of monitor and control events is normally to the nearest second.

2.2.7 *Phase Calibration Generators*

The stability of the receivers used to detect signals from extra-galactic radio sources at the various DSN antenna sites is critical, but often difficult to control because of the extreme and exposed environment of the antenna and its electronics. Performance of very-long baseline interferometry (VLBI) measurements can be improved by comparing phase variations in received signals to a stable calibration tone locally generated in the detection bandwidth.

The Phase Calibration Generator (PCG) system provides these high stability calibration comb tones. A comb spectrum with a fixed 1.0 MHz line spacing can be injected into the feedcone or microwave waveguide ahead of the S-band and X-band low noise amplifiers (LNAs) in the DSN 34 m HEF and 70 m antennas when required. A similar spectrum can be injected into the waveguide ahead of the L-band LNAs in the 70 m antennas.

PCG receiver and comb generator stability tests were performed at the JPL Frequency Standards Test Laboratory both in a stabilized temperature environment and with temperature cycling. The averaged Allan Deviation from the 15 units tested is shown in Figure 4. Based on knowledge of temperature sensitivity of the PCG and the environmental requirements for the locations where they are installed, a curve showing the estimated installed performance of the PCG at a typical DSN site has been calculated and is also shown in Figure 4.

2.3 *Frequency and Time Synchronization*

DSN frequency and time synchronization is referenced to UTC using common-view GPS time transfer. This technique allows the direct comparison of two clocks at widely separated locations by canceling out the effect of GPS clock performance and most media effects, see Figure 5.. The DSN GPS receiver takes the time difference between the DSN master clock and the time obtained from one or more GPS Satellites (including propagation delay) and creates a data file. NIST maintains a similar database between UTC and all GPS satellites. The NIST database is queried periodically and the DSN Time Analyst uses the data and a weighted averaging technique to derive time offsets. Frequency offsets are derived using a moving average barycentric filter. The resultant information is used to adjust the DSN frequency standards to keep them within the frequency and time specification.

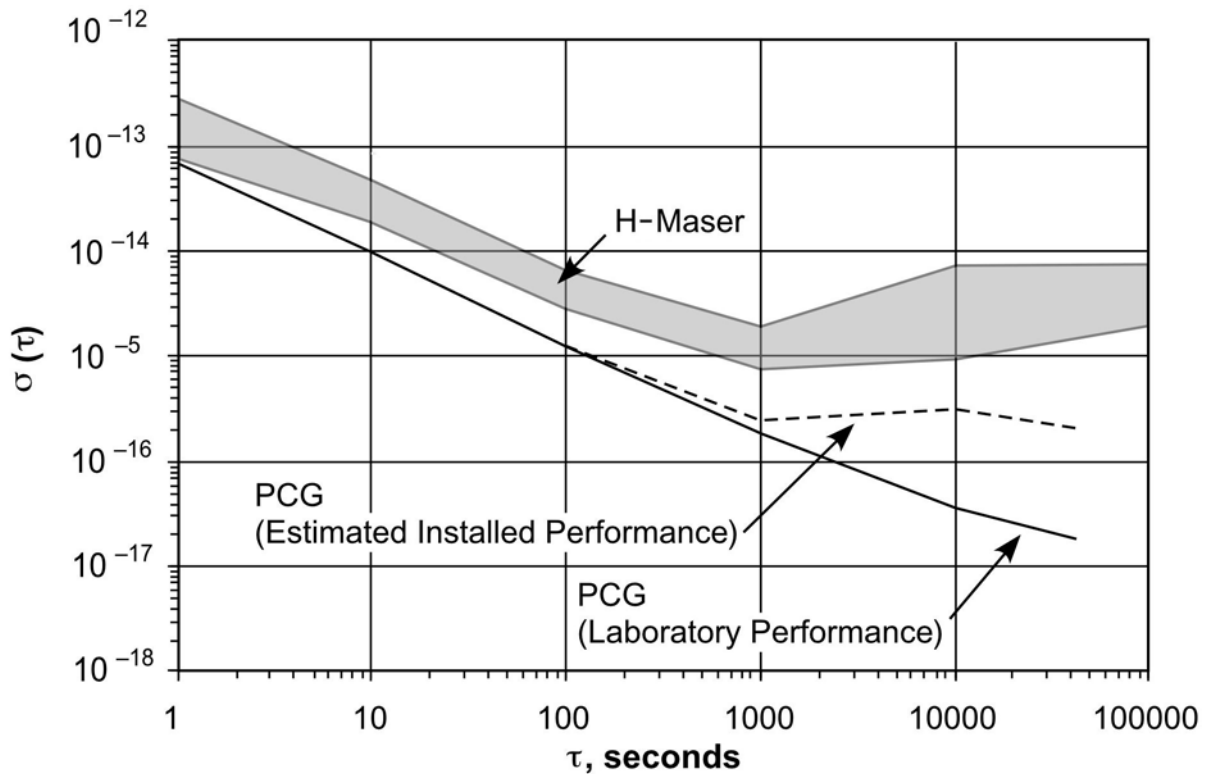


Figure 4. S-band and X-band Phase Calibration Generator Stability.

2.4 Adjustment of DSN Time to UT1

The Earth's rate of rotation is not uniform. It is affected by gravitational effects of the sun, moon, and planets, tidal effects, and several other mechanisms. The time scale based on the Earth's rotation, corrected for polar motion, is called UT1 and is maintained by the International Earth Rotation Service (IERS), <http://www.iers.org/>. UT1 enables proper aiming of telescopes and radio-telescopes (including DSN antennas) at celestial objects.

The mean solar day as determined from the UT1 time scale is approximately 2 ms longer than 86,400 SI seconds established by atomic clocks. By international agreement, the UT1 and UTC time scales are kept synchronized within ± 0.9 seconds by step-time adjustments of exactly one second (leap seconds). Notification to perform this adjustment is received from the IERS between 30 and 60 days before the adjustment is required. Leap seconds are added or subtracted, usually at the end of December or June, at the end of the day and set, as described below. DSN users must be aware of the potential for interference between time adjustments and sequences of time-critical events. Table 3 provides the sequences of time codes that occur during leap second adjustments.

Table 3. DSN Leap Second Adjustments.

Day	Second	Time
Leap Second Add		
n	t	23:59:59
$n + 1$	$t + 1$	23:59:59 *
$n + 1$	$t + 2$	00:00:00
$n + 1$	$t + 3$	00:00:01
Leap Second Subtract		
n	t	23:59:58
$n + 1$	$t + 1$	00:00:00
$n + 1$	$t + 2$	00:00:01

* Note: The existing system does not meet the accepted standard of 23:59:60 for leap second rollover. The accepted standard will be implemented in the new timing system summarized in Section 3.1.

3 *Proposed Capabilities*

The following paragraphs discuss capabilities that have not yet been implemented by the DSN but have adequate maturity to be considered for spacecraft mission and equipment design. Telecommunications engineers are advised that any capabilities discussed in this section cannot be committed to except by negotiation with the Interplanetary Network Directorate (IND) Plans and Commitments Program Office.

3.1 *New Master Clock and Time Distribution System*

The implementation of a new master clock and time distribution system for the DSN is in progress with a completion date scheduled for 2004. The new timing system will provide improved performance, expandability, and maintainability compared to the existing system. A significant difference will be replacement of the existing triple-redundant clock with majority vote by a single clock and synchronized backup clock. This reduction in complexity coupled with improvements in electronic design will provide a significant increase in availability. Significant characteristics of the new system are provided in Table 4.

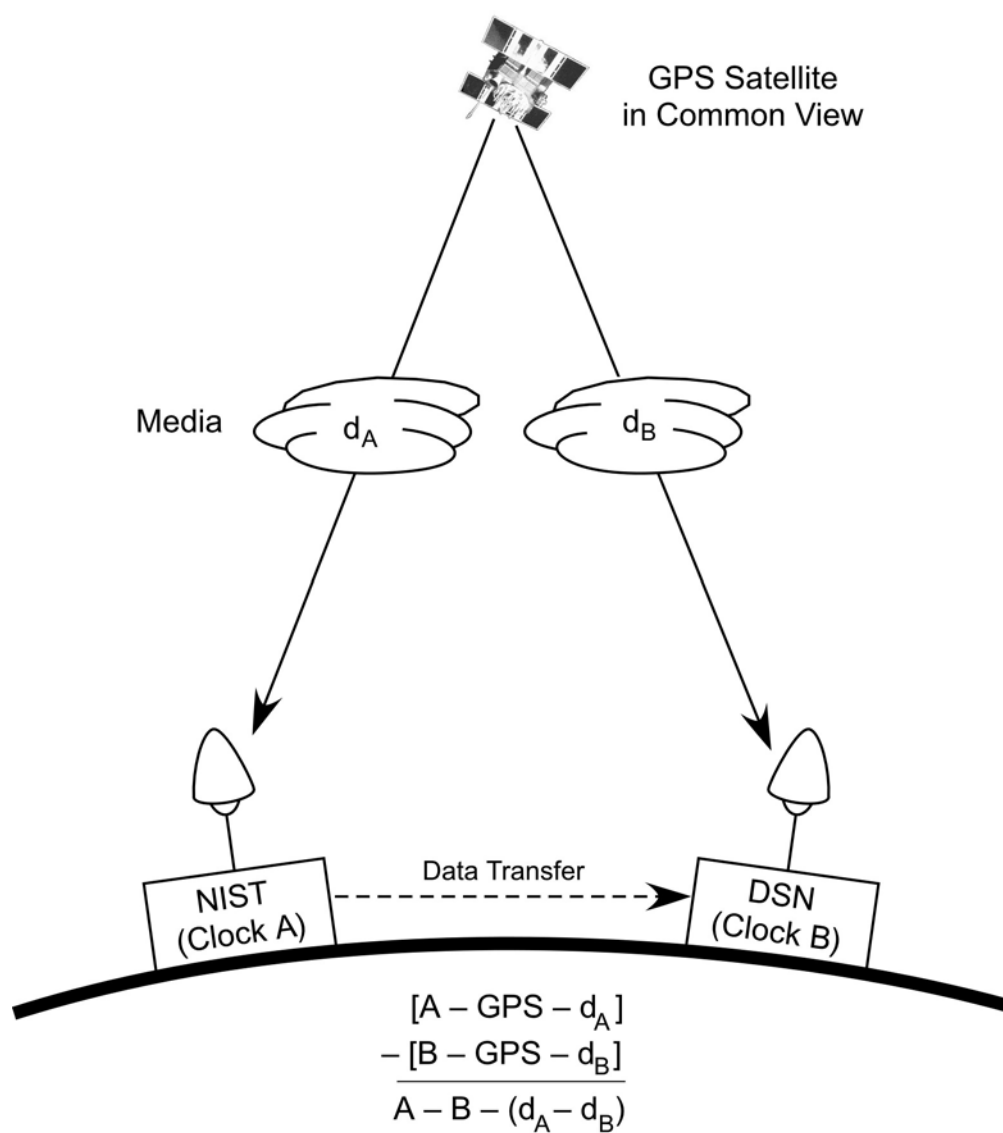


Figure 5. Common View GPS Time Transfer.

Table 4. New Master Clock and Time Distribution Performance.

Parameter	Existing Capability	Proposed Capability
Master Clock Setability	50 ns	10 ns
Timing Pulse Jitter (1σ)	2 ns	≤ 50 ps
Time Offset between master clock and users	< 100 ns	< 10 ns
TCT Holdover	None	12 hours
Leap Second Adjustment	Non-standard	Standard

3.2 *Improved Frequency Distribution at DSCCs*

A replacement for the frequency distribution equipment at the DSN complexes has been proposed that would provide photonic distribution to supplement the existing frequency distribution employing coaxial cables. This will provide improved moderate term stability and spectral purity by distributing frequencies as high as 1 GHz in contrast to the present 100 MHz. The visibility of improved spectral purity to DSN users will depend on the implementation of other equipment that makes use of the higher reference frequencies.

3.3 *Ka-band Phase Calibration Generator*

A Ka-band phase calibration generator has been developed and is being evaluated on a 34-m BWG antenna (DSS 25) for installation on the remaining BWG antennas. This new design generates stable comb tones spanning the frequency range from 3 GHz to 40 GHz. The proposed performance capabilities are summarized in Table 5.

Table 5. Ka-band Phase Calibration Generator.

Parameter	Proposed Capability
Stability (Allan Deviation)	
1 s	5×10^{-14}
10 s	8×10^{-15}
100 s	1.0×10^{-15}
1000 s	1.2×10^{-16}
$10,000 \text{ s} < \tau < 100,000 \text{ s}$	$< 5 \times 10^{-17}$
Amplitude Flatness	± 1.7 dB, 32 — 33 GHz
Comb Spacing	1 MHz or 5 MHz selectable